REPORT

OF THE

NASA
SCIENCE DEFINITION TEAM

FOR THE

MARS RECONNAISSANCE ORBITER
(MRO)

February 9, 2001

CONTENTS

REPORT OF THE NASA SCIENCE DEFINITION TEAM FOR THE MARS RECONNAISSANCE ORBITER

February 9, 2001

1.0 PREAMBLE

NASA has determined that its Mars Exploration Program (MEP) will pursue launch of an orbiter to Mars in the 2005 launch opportunity. Under the direction of Dr. James B. Garvin, the NASA Mars Exploration Program Scientist, a Science Definition Team (SDT) was formed for this orbiter mission, provisionally called the Mars Reconnaissance Orbiter (MRO). Membership and affiliations of the SDT are given in Appendix 1. Dr. Richard W. Zurek and Prof. Ronald Greeley co-chaired the SDT.

The purpose of the SDT was to define the:

- Scientific objectives of an MRO mission to be launched to Mars in the summer of 2005, building on the recommendations from the Mars Exploration Payload Analysis Group (MEPAG) and from the National Research Council Space Studies Board Committee on Planetary and Lunar Exploration (COMPLEX). Key references are: 1) MEPAG, 2000, *Mars Exploration Program: Scientific Goals, Objectives, and Priorities*; and 2) COMPLEX, 1994, *An Integrated Strategy for the Planetary Sciences: 1995–2010;* 1996, *Review of NASA's Planned Mars Program;* 1998 *Letter Review: Assessment of NASA's Mars Exploration Architecture*.

- Science requirements of instruments that are most likely to make high priority measurements from the MRO platform, giving due consideration to the likely mission, spacecraft and programmatic constraints on the '05 MRO mission. As a starting point, the SDT was to assume spacecraft capabilities similar to those described in the '03 Mars Surveyor Orbiter (MSO) study, but should also specify any additional spacecraft capabilities required to support high-priority measurements.

The MSO study referenced above was conducted in April–July 2000, as the principal competitor for launch in 2003 of the Mars Exploration Rover mission ultimately selected by NASA. In the MSO study, a science payload was provisionally selected and included a visible near-infrared imaging spectrometer, a high-resolution camera, an ultraviolet imaging spectrometer, and the redesigned Mars Climate Orbiter (MCO) instruments, namely the Pressure Modulator Infrared Radiometer (PMIRR) and the Mars Color Imager (MARCI). The latter was actually a dual-camera system with both wide angle (MARCI WA) and medium (resolution) angle (MARCI MA) cameras.

The SDT was directed to complete its work by the end of January 2001. This rapid turn-around was required in order to prepare requests for proposals; specifically, an Announcement of Opportunity (AO) for science investigations, and a Request for Proposals from industry for the flight system, both to be released in early 2001. The SDT was further directed to consider specifically:

- Recovering the PMIRR and MARCI investigations lost with MCO
- Mapping surface mineralogy using near-infrared hyperspectral imaging
- Obtaining high resolution images of the surface
- Carrying additional science payload as feasible

The initial SDT meeting was held via videocon and telecon on December 21, 2000. At the meeting, the JPL MRO Project Team described a reference mission which included: a) target payload mass, power, and volume envelopes, derived by updating the ’03 MSO study; b) mission designs, including orbit insertion options and potential orbits achievable with a baselined Intermediate-Class Launch Vehicle; and c) issues and concerns regarding various payload instrument candidates, such as instrument mass, cooling requirements, fields of view, and electromagnetic interference (EMI). Following discussions of the potential science objectives of an ’05 mission, subgroups of the SDT were formed to foster detailed discussion within five major areas [SDT subgroup leaders are identified in brackets]:

- Atmospheres [J. Barnes];
- Surface Mineralogy and Composition [initially, L. Soderblom; later J. Farmer, J. Mustard, and S. Murchie]
- Subsurface Sounding [R. K. Raney and S. Clifford, with support from a group led by D. Beaty in the JPL Mars Program Office]
- Imaging [R. Zurek with M. Carr and M. Malin]
- Gravity and Magnetism Studies [S. Smrekar]

These subgroups addressed specific issues in more detail through telecons and email exchanges.

The second and major meeting of the SDT was hosted at Arizona State University, January 18–20, 2001. The JPL Project Team reported back on actions identified at the December SDT meeting and on issues which had arisen during further study of spacecraft accommodation and of mission design. Subsequent discussion was organized around the subgroup science areas, with reports from the subgroup leads recommending prioritization and key issues within their respective areas. Building on these appraisals, the SDT then considered potential combinations of candidate investigations in order to confirm that there were science payloads, fitting within the described MRO constraints, which would credibly address high-priority science objectives. The meeting concluded with further discussion of the final recommendations, including some prioritization across all science areas within the context of the MRO mission.

This report summarizes the activities and recommendations of the SDT. Section 2 identifies the key science questions that the SDT believes can be addressed by MRO in the 2005 launch timeframe. Section 3 lists specific recommendations of the SDT to the NASA Mars Exploration Program, followed by highlights in Section 4 of the discussions that led to the SDT recommendations. Section 5 summarizes recommendations by the SDT regarding some broader programmatic issues. Supporting material can be found in the Appendices. In particular, Appendix 2 traces the MRO science questions and candidate investigations to the MEPAG measurement recommendations, while Appendix 3 lists sample payloads which the SDT used to assess the range of scientifically credible options still within expected limits of the MRO spacecraft and mission capabilities.

In its deliberations, the SDT emphasized science requirements. *The SDT did not consider requirements for reconnaissance in preparation for eventual human exploration of Mars or for characterization of hazards at potential landing sites for future robotic missions.* Thus, the SDT identified measurements needed to identify landing sites of high scientific interest, but did not discuss the minimum measurement requirements needed to characterize hazards at such sites. Establishing such minimum requirements must be done in the context of the projected capability and design of the landing system; these requirements are being addressed separately by a group convened by the JPL Mars Exploration Program Office.

2.0 SCIENCE OBJECTIVES FOR THE MRO

The Mars Exploration Program has adopted a “Follow the Water” strategy, which provides the crosscutting theme through the Mars Exploration Program’s four main areas of emphasis: Life, Climate, Geology, and Preparation for Human Exploration of Mars. The SDT focused on the first three of these areas, which motivate the core science investigations. The “Follow the Water” strategy is very ambitious, and any single mission can accomplish only a part. Also, the degree of progress that can be made in any one area, no matter how high its scientific priority, often depends critically on the progress of instrument technical development. This is particularly important for the MRO mission as described by the Project to the SDT, as it appears to have a doable, but still challenging schedule for spacecraft and payload development, assembly, test and launch. Furthermore, although the SDT did not discuss mission budget in any detail, there are concerns that the funding available cannot support substantial instrument technical development. The MRO budget portion for the science payload appears to have been taken from the ’03 MSO study (adjusted for inflation). That study emphasized flight-proven instrument design and hardware, due to the even more demanding schedule required for launch in 2003.

With these potential constraints in mind, the SDT has divided the recommended science objectives for the MRO mission into two categories. The SDT recommends that *the core objectives (Group I) must be addressed in a significant way by any payload selected for MRO*. However, the SDT believes that instruments addressing these core scientific objectives do not require the full capabilities allocated for payload in the MRO reference mission. Within the remaining resources, *NASA should consider selection of investigations that address additional high priority scientific objectives (Group II).*

The scientific objectives recommended for the MRO mission are then:

Group I:

- Recover the MCO atmosphere and climate science objectives:
  - Characterize seasonal cycles and sample diurnal variations of water, dust, and carbon dioxide to understand processes of present and past climate change.
  - Characterize global atmospheric structure, transport, and surface changes to elucidate factors controlling the variable distributions of water and dust.
- Search for sites showing evidence of aqueous and/or hydrothermal activity:
  - Search for localized areas showing past aqueous mineralization.
  - Observe detailed geomorphology and stratigraphy of key locales to identify formation processes of geologic features suggesting the presence of liquid water.
- Explore in detail hundreds of targeted, globally distributed sites:
  - Characterize in detail the stratigraphy, geologic structure and composition of surface features to better understand the formation and evolution of complex terrain.
  - Distinguish processes of eolian and non-eolian transport and surface modification.

Group II:

- Detect the presence of liquid water and determine the distribution of ground ice in the upper surface, particularly within the near-surface regolith.

- Provide atmospheric observations in addition to the MCO capabilities (i.e., PMIRR and MARCI Wide Angle) to further define atmospheric structure and circulation.

- Characterize the gravity field in greater detail to understand better the geologic history and structure of the crust and lithosphere.

- Explore additional ways of identifying sites with high scientific potential for future Mars landed investigations.

(The listings within Group I and Group II do not imply priority.)

The strategy outlined above is the recommendation of the SDT. However, it was not unanimous, in part because there are at least two views of what reconnaissance means in the context of an ’05 Mars mission. One view is that it should be “reconnaissance in force”, in the sense that the mission and spacecraft resources are fully dedicated to one or two primary investigations (e.g., ultra-high-resolution imaging or subsurface sounding). In this view, one attempts to bring to closure one or two primary scientific objectives, as completely as can be achieved from orbit (within the foreseeable future).

The second—and majority—view of the SDT was that an ’05 orbiter mission should be one of exploration and discovery in a few carefully chosen areas, rather than detailed characterization in support of a single objective, even as the mission focuses on a single theme (“Follow the Water”). There is much that we do not know or understand about Mars, and a significant effort in a few well–chosen, high priority areas was judged by a majority of the SDT to be most likely to advance substantially our understanding of Mars. Furthermore, a cross-disciplinary MRO mission will provide—together with 2001 Mars Odyssey and ’03 Mars Express—the critical data needed to define such highly focused “closure” missions, each of which might well require the equivalent of the MRO spacecraft and mission resources, as part of the ongoing Mars Exploration Program.

In summary, the SDT recommends that the MRO mission address each of the Group I objectives and, as resources permit, one or more of the Group II objectives.

3.0 SDT RECOMMENDATIONS TO NASA

3.1 Mission and Spacecraft:

Specific recommendations of the SDT are as follows [see Section 4.1]:

3.1.1 *The MRO mission should plan to observe hundreds of different sites spread across the planet at the high spatial resolutions recommended for its science payload.*

- 3.1.1a Ensure that the spacecraft can provide adequate pointing stability and sufficiently accurate navigation to acquire high spatial resolution observations.
- 3.1.1b Ensure that a context imager, a high-resolution imager, and an imaging spectrometer are <u>able</u> to observe the same targeted locale at the same time (i.e., nested observing patterns).
- 3.1.1c Most targets should be chosen once the spacecraft is in orbit; some will be chosen based on data from past missions, MGS, 2001 Mars Odyssey, and Mars Express and on programmatic considerations (e.g., landing sites for a spacecraft to be launched in 2007).

3.1.2 *At the same time, the MRO mission should provide the systematic mapping required to recover the MCO atmospheric and climate science objectives.*

- 3.1.2a Provide a reasonable near-polar, low–altitude, and low eccentricity orbit (see 3.1.3).
- 3.1.2b The MRO Project should ensure that EMI (from the spacecraft or other instruments) does not preclude acquisition of key data by the science instruments selected for MRO.

3.1.3 *The SDT recommends the following orbit parameters for MRO:*

- 3.1.3a A 200 x 400 km near-polar orbit after aerobraking to support high-resolution surveys of targeted areas. The periapsis of this orbit should rotate around the planet to provide global access for high-spatial-resolution targeted observing.
- 3.1.3b The Project should plan—and investigations responding to the AO should assume—that the elliptical orbit phase will be followed by transition (at a time to be determined) to a near-polar, near-circular orbit at altitudes ≤ 400 km.
- 3.1.3c Sun-fixed, near-polar orbits with a targeted mean local solar time of 3:00 to 3:15 p.m. of the equatorial crossing node (i.e., true local times extending to ~ 4:00 p.m.).

3.1.4 *The SDT endorses the planned Primary Mission with one Mars year of observations with the science payload, and recommends a goal of an extended mission partially covering a second Mars year* while allowing for support of later Mars missions. (Extended mission is not in the present budget.)

- 3.1.4a The primary mission duration of one Mars year must provide critical observations in all Mars seasons, so that key seasonal cycles are adequately characterized.
- 3.1.4b While support of spacecraft launched in 2007 takes precedence over the desired extended mission, planning of the Relay Support Phase must involve the science teams of all affected missions, especially where mission trades are based on science.
- 3.1.4c The Project should investigate the feasibility of continuing some MRO science observing during the Relay Support Phase for the 2007 opportunity missions, particularly when those observations complement or provide context for the landed science investigations. This would be part of an extended mission.

3.1.5 *The SDT endorses enthusiastically the proposed data return targets of 12–110 Gbits per day,* depending upon the Earth-Mars range (36 Gbits/day on average for one Mars year). The SDT advises the MRO Project to preserve and, if possible, enhance this capability, in order to achieve a goal of ~ 1 % of Mars areal coverage at high spatial resolution.

3.1.6 *The SDT recommends that the MRO mission exploit the scientific potential of <u>spacecraft</u> systems,* acknowledging that the limiting factor may be funding of the science teams.

- 3.1.6a Ensure, if resources permit, that the spacecraft accelerometers used for aerobraking will return adequate data for scientific analysis.
- 3.1.6b Ensure that, if resources permit and if an ultrastable oscillator (USO) is flown for UHF relay, the USO is available for radio science investigations on MRO and future orbiters; however, the SDT does not recommend adding an independent USO.

3.2 Group I Science Investigations:

The SDT recommends the following to NASA:

3.2.1 *Fly the redesigned PMIRR (PMIRR-MkII) and the MARCI Wide Angle (WA) camera* under the direction of the previously selected PMIRR and MARCI science teams [4.2, 5.1].

3.2.2 *Fly the MARCI Medium Angle (MA) camera designed for MSO as a facility experiment* to ensure context imaging for a high-resolution imager and an imaging spectrometer [4.4, 5.1].

3.2.3 *Select a visible near-infrared imaging spectrometer* able to identify unambiguously key aqueous minerals of interest. Requires surface footprints ≤ 50 m/pixel in ground scale from 400 km orbit altitude, with swath widths and downtrack traverses ≥ 10 km. Requires observations with adequate signal to noise in the 0.4 to 3.6 micron range [4.3].

3.2.4 *Select a visible imaging camera* that can observe from near-circular orbits at altitudes of 300 to 400 km and from an elliptical 200 x 400 km orbit. Required surface resolutions are: 60 cm/pixel and swath widths ≥ 6 km from orbital altitudes of 400 km, and 30 cm/pixel and swath widths ≥ 3 km from 200 km [4.4].

3.2.5 *Explore* means of augmenting the return of 2001 Mars Odyssey THEMIS VIS full multi-color imaging data to achieve the multi-spectral objectives of the MCO MARCI MA investigation and to support early targeting of the high-resolution imaging and imaging spectrometer instruments recommended for flight on MRO [4.3].

3.3 Group II Science Investigations:

The SDT recommends the following to NASA:

3.3.1 *Select a facility science team to analyze the spacecraft accelerometer data*, as resources permit and assuming that the spacecraft aerobrakes at Mars, as proposed by the JPL Project [4.2].

3.3.2 *Select a facility science team to analyze tracking data for gravity studies*, as resources permit and assuming the spacecraft spends considerable time in its prime orbit at altitudes ≤ 300 km. [4.6]

3.3.3 *Fly a comprehensive subsurface sounding radar package as part of the <u>Mars Exploration Program</u>*. If not on MRO, then plan for flight no later than the 2009 launch opportunity, which will allow ample time to build on the ’03 Mars Express MARSIS observations. [4.5]

3.3.4 *For MRO, consider selection of a subsurface sounding radar* able to detect water unambiguously and to profile ice in the topmost 1 km of subsurface with approximately 10 m vertical resolution. This near-surface capability is required; the ability to profile deeper (to ~ 5 km with 100 m vertical resolution) is desired, depending on its impact on spacecraft accommodation [4.5].

3.3.5 *Consider* selection of atmospheric sounding complementary to that of PMIRR-Mk II. The ability to profile water vapor over an extended altitude range and in a very dusty atmosphere is required; ability to measure winds at some altitudes <100 km is highly desired [4.2].

3.3.6 *Consider selection of a facility science team for radio science,* as resources permit and <u>if</u> MRO carries an USO [4.2].

3.3.7 *Consider* other investigations addressing Mars Exploration Program high priority science objectives, as justified by gain in science return against the impact on spacecraft accommodation and mission resources [e.g., see 4.3].

3.4 Programmatic Issues

The SDT recommends the following to NASA [see Section 5]:

3.4.1 *All science instruments solicited by the AO be PI-provided* [5.1], except for the context imager [4.4].

3.4.2 *NASA should form an MRO Project Science Group (PSG)* to be chaired by the MRO Project Scientist. Members of the PSG would include the Project (and Deputy Project) Scientist, the NASA MRO Program Scientist, the Principal Investigators and Team Leaders of the selected science investigation teams. Ex officio members would include the NASA Mars Exploration Program Scientist and the JPL Mars Program Chief Scientist.

The MRO PSG should:

3.4.2a Make recommendations to the Project and to NASA on all major options affecting science.
3.4.2b Adjudicate conflicts between the science investigations and resolve conflicts with the Project.
3.4.2c Coordinate the choice of sites for some targeted observations [5.1].

3.4.3 *Preparations should be made for the distribution and analysis of the potentially huge MRO volumes of observational data and derived data products.*

3.4.3a NASA, the JPL Mars Program and the MRO Project should give special attention to understanding and covering all legitimate costs of data distribution, processing and analysis [5.5].
3.4.3b A guiding principle for the design of the ground data system should be that the Science Teams control distribution and processing of their investigation’s data, as consistent with the NASA data rights policies. Modifications in design philosophy should be discussed with NASA and the MRO Science Teams. [5.2]
3.4.3c The standard Mars Program data policy should be applied to the MRO Project and Investigators [5.3].

3.4.4 *Preparations should be made to select science investigators for MRO*.

3.4.4a The PMIRR and MARCI Science Teams should be reformed as previously selected [5.1].
3.4.4b The MRO AO should solicit PI-led Science Teams as part of instrument selection and facility science teams where appropriate [5.1].
3.4.4c Team leaders of selected facility science teams (or their designates) should be brought onboard as soon as possible [5.1].
3.4.4d An AO for MRO Participating Scientists should be included, with selected investigators coming onboard no later than launch of the MRO [5.4].
3.4.4e NASA should explore the possibility of adding interdisciplinary investigators at the program level (i.e., across individual mission boundaries) [5.4].

In this document, cross-references to the above recommendations are indicated as [R3.N.Mx]. References to sections are given by [N.M].

4.0 Discussion

4.1 Mission and Spacecraft

There was considerable discussion of what the mapping orbit should be, other than that it should be a relatively low-altitude, polar, sun-fixed (or nearly so) orbit. Whether elliptical or near-circular, the polar orbit enables global access [R3.1.2a] for the high-resolution imaging instruments and for the global mappers (i.e., the atmospheric sounders and possibly the radar). The Project updated the analysis of the 200 x 400 km elliptical orbit. In the ’03 MSO study, this orbit was achieved by a modest raise at the end of aerobraking of the periapsis altitude to 200 km, with apoapsis remaining at 400 km. This elliptical orbit would have served as a transition orbit on MSO for high-spatial-resolution imaging prior to raising periapsis to achieve a near-circular 400 km orbit, essentially the MGS orbit altitude.

The Project also examined the characteristics of a near-circular orbit at 300 km. The penalty for these lower altitude orbits (apoapsis < 400 km) is the propellant required to bring the apoapsis down following aerobraking. Furthermore, once there, more fuel than currently budgeted would be used in lower altitude circular orbits (≤ 300 km) for station-keeping and to counteract decay in periapsis altitude. The mass (estimated as ~ 20 kg) for this extra fuel would currently have to come from the MRO payload allocation. Should spacecraft mass margins prove to be more robust than anticipated, these lower altitude near-circular orbits should again be considered, including altitudes as low as 300 km. *The SDT recommends the 400 km apoapsis orbits because they preserve the payload mass allocation [R3.1.3]*

The main advantage of the 200 x 400 km elliptical orbit over the 400 km near-circular orbit is the potential increase in ground spatial resolution by up to a factor of 2. High-resolution observing can still be targeted globally as a slight orbital inclination will move the periapsis latitude around the planet. For the Project’s candidate orbit, the periapsis would rotate once around the orbit (and planet) every 60 days. The main drawback is the variation of ground speed and image ground resolution, with the latter degrading by up to a factor of two every other month as periapsis moves across the night side. This variable viewing geometry does affect the systematic mapping instruments, which would prefer a more circular orbit and which could not easily accommodate a more elliptical orbit than the one proposed here [R3.1.2a].

Given its advantage, the SDT recommends that the elliptical orbit be baselined, [R3.1.3a] pending further analysis. However, the SDT also recommends that the AO require that the MRO instruments be able to provide meaningful data from near-circular orbits at altitudes of 300 or 400 km [R3.1.3b]—since the latter is known to work—so that late-breaking surprises do not invalidate the scientific credibility of the mission. At some point planetary quarantine requirements will necessitate raising the MRO periapsis altitude to ~400 km anyway, so there will be fuel onboard to do this. The timing of the transition to the near-circular orbit can be decided during the primary mission itself; it is possible that the entire primary mission (i.e., one Mars year) would be spent in this orbit.

The other major orbit issue was the local time of the orbit, whether near-circular or elliptical. Since much of the Martian surface intrinsically has low visual contrast, high-resolution imaging benefits from the increased surface contrast provided by low sun angles, especially at low latitudes (presently preferred by solar-powered landers). This argues for a late afternoon local mean solar time near 4 p.m. This time provides the best viewing near the equator where the MGS MOC observations are limited by the 2 p.m. local mean solar time orbit of MGS, even with the annual ±40-minute change in true local solar time due to the eccentricity of the Mars orbit. The best quality MOC images are thus taken at nonequatorial latitudes where seasonal changes provide lower sun angles.

Meanwhile, imaging spectrometry desires earlier times (< 3 p.m.) which provide more reflected light and so data with better signal-to-noise. Atmospheric sounders try to avoid true local times ≥ 4 p.m., as the diurnally varying temperatures of the surface and lower atmosphere tend to be the same at that time of day. This loss of thermal contrast between the atmosphere and ground significantly degrades on-planet sounding for dust and trace gases. Given the annual variation of local true solar time and seasonally varying sun angles away from the equator, *the SDT recommends an equator-crossing local mean solar time of 3 – 3:15 p.m. [R3.1.3c]*, as a reasonable compromise between various, high priority science investigations. This should be revisited once instruments are selected.

There was some discussion of how to best use the targeting opportunities that MRO would provide daily once in orbit. First, the AO needs to describe clearly that, even with the substantially increased data downlink capability proposed for MRO, the requirements for high-spatial resolution with several instruments and with good regional context imaging may limit observations to a few targeted sites per day (perhaps 2–10, depending on Earth-Mars range). The SDT considered whether it was better to image a dozen or so sites multiple times to build mosaics of extended locales and perhaps to view the same places at different illumination. *The SDT recommends the alternative choice, which is to view literally hundreds of sites [R3.1.1].*

In support of this choice, the SDT has recommended minimum swath widths, assuming any targeted site will be viewed only once (unless it is exceptionally interesting, of course). This is operationally easier to accommodate (orbit latitudes and longitudes do not have to be precisely repeated) and also reflects the fact that to date we have seen very little of Mars at even the resolution of the MGS MOC. (Note that the present plan is that the spacecraft would enable off-nadir, cross-track pointing, but would not point instruments off-nadir in the down-track direction; this constraint should be noted in the AO material.) Some targeted sites would be chosen based on past landing sites and on programmatic plans for the 2007 missions and beyond. However, the SDT believes that the MRO Project should preserve considerable flexibility in choosing the surface sites to be imagined, so that the mission can respond to what MGS, 2001 Mars Odyssey, NOZOMI, Mars Express, and MRO itself will reveal about Mars. *The SDT recommends that the selection of sites should involve the MRO Science Team and others chosen by NASA to represent interests of future missions [R3.1.1c, R3.4.2c].*

4.2 Atmospheric Science

The SDT reviewed the major redesign of the Pressure Modulator IR Radiometer (PMIRR) which was carried by the ill-fated Mars Observer and by the Mars Climate Orbiter spacecraft. *The SDT endorses the new design (PMIRR-MkII) [R3.2.1]*, as it credibly addresses the same science measurement objectives as did the earlier instruments and, in doing so, it has reduced dramatically the required spacecraft resources. For instance, the instrument mass has been reduced from > 40 kg to < 10 kg and yet retains the key sensitivity to water, dust and temperature. The one concern expressed is that the high priority water vapor mapping capability of PMIRR/PMIRR MkII can be significantly degraded during the more dusty conditions which have occurred in the Mars atmosphere in the recent past (e.g., as in the Viking mission).

That sensitivity led the SDT to consider and then recommend the possible addition of sounding capability [R3.3.5] complementary to the PMIRR MkII instrument. Recent technical advances in submillimeter sounding techniques provide the possibility of limb and nadir sounding for water and temperature unaffected by atmospheric dust, with vertical resolutions of order 10 km and throughout an extended altitude range of 0–100 km. Depending upon spacecraft pointing capabilities, these sounders may also enable wind measurements with a precision of ± 15 m/s at 2–3 levels above 40 km altitude. Wind speeds at those heights will be strong enough in some seasons that this precision can provide a very strong constraint on wind calculations based on observed temperature/pressure gradients and on model simulations of atmospheric circulation.

It appears that a submillimeter sounder would require on order of 10 kg, 30W, which when combined with the PMIRR MkII would still be a package smaller (< 20 kg, ~ 36W) than the MCO PMIRR (40 kg, 44 W). There may be other technical approaches, as well. Such sounding capability is not a substitute for the PMIRR-MkII investigation, as the latter has higher vertical resolution (~ 5 km, less than typical atmospheric scale heights), polar energy balance monitoring capability, and the ability to profile the atmospheric dust distribution, which is key to the thermal driving of atmospheric circulation and transport.

The MARCI Wide Angle camera flown on MCO had two UV channels, in part to map atmospheric ozone, which in the Mars atmosphere is photochemically anticorrelated with water. The MARCI Wide Angle also had several color channels to help separate dust from water ice in Martian aerosols and on the Martian surface. *The SDT recommends flying a rebuilt MARCI Wide Angle camera [R3.2.1]*, as its low-spatial-resolution, limb-to-limb viewing remains an important means of characterizing Martian weather and providing context for the atmospheric sounders.

The SDT also considered the inclusion of ultraviolet imager/spectrometer instruments. Such an instrument, the UV Imaging Spectrometer was included in the '03 Mars Surveyor Study to study upper atmospheric structure and processes as a means of understanding the loss to space of water vapor and other gases [CA4, Appendix 2]. The SDT placed higher priority on the submillimeter sounding described above, due to its sensitivity to atmospheric water from 0–80 km altitude, its potential for wind measurement, and the timing of the MRO mission. There are highly capable upper atmospheric experiments on NOZOMI (formerly PLANET B) and Mars Express. These missions arrive at Mars in 2004, just before the minimum in solar cycle activity, while MRO would arrive just after. Thus, *the SDT does not recommend experiments focusing on atmospheric escape for the MRO opportunity*. *The SDT does recommend that such investigations be considered for a future orbiter* in the Mars Exploration Program that will observe Mars when solar cycle activity is near its maximum.

The SDT recommendations concerning the spacecraft accelerometers [R3.1.6a, R3.3.1] used for aerobraking are meant to ensure that the extended vertical and latitudinal sampling that require full use of the onboard accelerometer precision is not lost. By extending the in situ profiling of the 100–170 km altitude region to different seasons for a range of latitudes (mostly in the southern polar region for MRO), these measurements will extend the scientific and engineering climatology established with MGS and (soon) with the 2001 Mars Odyssey. This will help support future spacecraft which aerobrake, aerocapture or enter the Mars atmosphere.

Radio science investigations, by analyzing atmospheric refraction of the radio signal as the spacecraft disappears into or emerges from eclipse by the planet, provide very high vertical resolution profiles (~200 m) in the lower atmosphere and an altitude location of the electron density peak, which reflects neutral atmosphere density. The orbit geometry is typically such that it is difficult with a single spacecraft to get good systematic global and seasonal coverage, even when the spacecraft has the ultrastable oscillator (USO) required to capture exit radio occultation profiles (as the spacecraft emerges from behind the planet). For that reason, it has lower priority than the globally mapping atmospheric sounders discussed earlier. However, radio occultation data also provide a means of calibrating the passive sounders, and this calibration assumes greater importance if only one spectral region (e.g., thermal infrared) is used to determine atmospheric density (i.e., temperature as a function of pressure).

The Electra Package proposed for flight on MRO to relay information to/from landed spacecraft from/to Earth via the orbiter may contain an USO. *If so, the SDT recommends that a radio science investigation for atmospheric characterization be considered for the MRO mission [R3.3.6, R3.1.6b]. If not, the SDT does <u>not</u> recommend adding an USO for MRO.* The SDT notes that radio science would have lower priority than the (submillimeter) atmospheric sounder described earlier, but would be more desirable if such additional sounding capability could not be added.

4.3 Surface Composition and Mineralogy

A key goal of the Mars Exploration Program has been to find past aqueous environments, which have the best potential for preserving signatures of past (and even geologically recent) life. Understanding the processing of surface materials throughout Martian history is also key to understanding the geological evolution of the planet's surface and interior. Thus, it is not surprising that considerable effort has been—and will be—expended to find locations of surface minerals formed in the presence of liquid water. The MGS Thermal Emission Spectrometer (TES) has been observing Mars in 3 km footprints with good spectral resolution and has detected three regions showing a hematite signature, but has found no region with carbonate or other hydrate signatures. The 2001 Mars Odyssey THEMIS experiment will search at higher spatial (~100 m footprints) but lower spectral resolutions (9 channels); the Mars Express OMEGA and Planetary Fourier Spectrometer (PFS) will search again at high-spectral, but intermediate (OMEGA: > 200 m) and low (PFS: > several kilometer) spatial, resolution. If these experiments can not find the desired locales, there is but one remaining combination of spectral and spatial coverage to attempt, namely a high-spatial- and high-spectral-resolution imaging spectrometer operating in the visible and near-infrared spectral range.

The measurement objectives for such a visible near-infrared imaging spectrometer are to provide accurate identification and precise discrimination of absorption bands due to aqueous surface minerals (ferric minerals, carbonates, clays, zeolites, etc.), particularly as dominated by fine-grained components. Additional objectives include detection of absorption due to bound or absorbed water and characterization of variations in ice absorption in terms of grain size. Overall, the objective is to resolve compositional differences associated with mesoscale environments. By terrestrial analogy, these may be at the scale of hot springs or paleolakes, thereby necessitating higher spatial resolution than those currently planned for flight. It is not just a matter of finding sedimentary material (sedimentary layers are known to exist from MGS MOC images), but rather sedimentary materials indicative of aqueous environments.

The SDT recommends the following requirements for imaging spectrometer measurement [R3.2.3]:

a) 0.4 – 3.6 micron wavelength range with ≤ 10 nm spectral sampling at wavelengths ≤ 2.6 nm and ≤ 20 nm sampling at other wavelengths;
b) Signal-to-Noise SNR>400 at 2.3 microns for representative targets (albedo of 0.3 at ≤ 30˚ phase angle)
c) Spatial footprints ≤ 50 m/pixel from 400 km with a required typical target swath size ≥ 10 km downtrack and crosstrack, with ≥ 20 km x 20 km desired.

These measurements are required to achieve the Group I science objectives discussed in Section 2. Augmentations, such as extending the wavelength range to 4.1 or 5 microns, should be considered [R3.3.7], with due concern given to the science gained for the spacecraft resources required for implementation. One particular accommodation issue might be the need for detector cooling to cover an extended wavelength range, where thermal emission is comparable in intensity to solar reflected light.

The need for context for these high-spatial-resolution, targeted measurements initiated a discussion within the SDT about the MARCI Medium Angle (MA) camera(s). The SDT judged the three-color capability of the MARCI MA design proposed as part of the MSO '03 study to be inadequate for identifying the most desirable places for targeting a high-resolution imaging spectrometer. Five color bands were regarded as a minimum requirement for a multi-spectral mapping camera. The nine-color MCO MARCI MA camera, with its 40 m/pixel spatial resolution, was not considered by the SDT as a candidate for re-flight on MRO because its core spectral capabilities are essentially captured by the 2001 Mars Odyssey VIS (camera), which is part of the THEMIS instrument. That VIS will record images in five multi-spectral bands at an improved 20 m/pixel spatial resolution. However, because it is not the highest THEMIS priority, only 10% of the planet is likely to be covered in five-color imaging, due to the restricted downlink capability of the ’01 MO orbiter. The Mars Express OMEGA instrument aims to acquire visible and near-infrared spectra over 50% of the planet after primary and extended orbiter missions. Unfortunately, much of those data will still be in the process of acquisition and analysis when MRO is ready to begin its own observations, and so would not be available to guide early targeting of the MRO instruments. THEMIS VIS data—even that acquired through a mission extended through 2004—could provide timely targeting guidance to MRO.

Thus, the SDT recommends that: a) the Mars Exploration Program continue to support the planned return of THEMIS VIS data; and b) opportunities for return of additional full (all 5) color VIS data be explored, including additional downlink time or an extended mission for the 2001 Mars Odyssey mission [R3.4.5]. An alternative is to re-fly the MCO MARCI MA camera, perhaps with the modifications introduced into the THEMIS VIS. The goal of that re-flight would be to extend multicolor coverage and not principally to support MRO targeting, since extensive coverage would likely come later in the mission when Mars is closest to Earth and data rates are high. This possibility was not rated as a Group I science objective, however, but was not discussed in depth by the SDT.

4.4 Imaging

Discussions about imaging and subsurface sounding were the most spirited and contentious of the deliberations by the SDT. For imaging, this was due to several factors: a) our inability often to interpret the MGS MOC observations (so how can we be sure that more data will bring a better understanding of Mars); b) the natural competition between the twin desires of obtaining more coverage and higher resolution imaging for a given downlink telecommunications capability; c) the difficulty of quantifying the expected science gain for any given increase in spatial resolution (or coverage, for that matter); d) the fact that significant increases over the MGS MOC spatial resolution are in a range that dramatically increases the instrument size and mass; and e) thus the realization that flight of an ultra-high-resolution camera might well require all the resources that the MRO spacecraft and mission could provide, thereby preempting other scientific investigations considered by the SDT to have equally high priority.

First, with regard to resolution and coverage: The MRO mission is presently scoped to return an order of magnitude (≥ 20) more data than MGS. That returned data volume could be used to obtain: a) MGS MOC-like spatial resolution over several per cent of the Martian surface; b) improved spatial resolution by a factor of 3 or more for ≤1 % of Mars; or c) ultra-high spatial resolution (≤20 cm/pixel) for a much smaller fraction of Mars. In terms of coverage, the MOC Narrow Angle camera had observed several tenths of a per cent of Mars by the end of the MGS primary mapping mission. Not all of this coverage is at the highest resolution, because—as MOC has demonstrated—spatial resolution and coverage can be <u>traded in orbit, if one has the required capability</u>. Higher spatial resolution than the MGS MOC could also be obtained simply by flying an MOC-resolution camera at lower altitude. In the 200 x 400 km orbit considered for MRO, this gains a factor of 2 in ground resolution over MGS. However, past experience suggests that a factor of 3–5 increase in spatial resolution is required to make significant advances over previous discoveries. Given the MRO data rate, such a high-spatial-resolution camera could cover an area comparable to the MGS MOC—though at substantially higher spatial resolution [scenario (b) above]—assuming a primary mission of one Mars year and an extended mission through part of a second Mars year.

The ground scale required for science depends on the scientific goal. Testing hypotheses of formation of the “gullies” and for complex layered terrain revealed by the MGS MOC requires the ability to distinguish amongst various possibilities, such as deposits from eolian, volcanic, and aqueous transport processes. For these studies, critical resolutions are in the range of 1–100 cm. The pixel resolution required to achieve these ground scales depends on the natural contrast of the surface being viewed (shadowing—i.e., low sun angles—can help), the light collecting area of the camera, signal-to-noise of the detectors, etc. Some understanding of what is being viewed—based typically on Earth analogs—can help interpretation, but can also be misleading.

In the MEPAG recommendations (Appendix 2) the climatology group asked for an order of magnitude increase in resolution over MGS MOC in part because the polar layered terrain has no terrestrial equivalent and because complex layered terrain seen by MOC elsewhere on the planet is not easily interpreted. The geology group in MEPAG requested spatial resolutions of ≥ 1 m (implying a ground scale of ≥ 0.5 m /pixel), emphasizing characterization of stratigraphy and surface morphology across more extended regions. It was emphasized to the SDT that the geology group was really arguing against the need for ultra-high spatial imaging (e.g., 20 cm/pixel), such as the climatology group had made, at the expense of extended—and often of contiguous—coverage.

The potential impact of doubling imaging spatial resolution (from a fixed orbital altitude) on the spacecraft is captured in the following table of estimates of the mass of an instrument potentially achieving the stated spatial resolutions. Different mass estimates reflect different trades in image quality and different assumptions about light-weighting of materials, principally for the primary mirror, whose size in these estimates varies from 45 cm to ~100 cm in diameter.

Table 4-1: Potential Payload Mass for High Resolution Imagers
(Estimates are for indication only)

	MOC	MSO Study	Estimates	units
Ground Scale @ 400 km @ 200 km	140 (MGS) 70	60 30	40 20	cm/pixel cm/pixel
Primary Mirror Diameter	35	45	100	cm
Telescope Size	40 x 80	60 x 150	120 x 240 ??	cm x cm
Instrument Mass	21 (MGS)	35–40	70–95	kg

Although large when compared to cameras flown on past Mars spacecraft, the telescope size can be accommodated within the shrouds of the Intermediate-Class Launch Vehicles being considered for MRO. Assuming these launch vehicles, the JPL Project provided two target payload masses from the reference design studies—70 kg and 86 kg—depending upon aerobraking options (and associated fuel loads) to be decided later.

With this as a background, the SDT debated whether the science to be gained justified the resources required. To see the details of feature morphology, size distribution and areal density of surface materials that might discriminate ultimately between hypothesized formation mechanisms may well require going to the 20–40 cm/pixel resolution. As seen above, this may mean that little else can fly on MRO (also see Appendix 3), so that accomplishing such ultra-high spatial resolution imaging requires a dedicated mission, now or later in the Mars Program. An alternate approach is to rely on past experience indicating that improvements in spatial resolution by factors of 3–5 are likely to show significant new features and will also begin to test hypotheses of surface processes.

The SDT majority adopted this latter view. Taking the recommendation of a 200 x 400 km orbit into account, *the SDT recommends selection of a high-spatial-resolution imager whose ground scale resolution is 3–5 times better than MOC. This recommendation is specified as 60 cm/pixel from an orbital altitude of 400 km and 30 cm/pixel from 200 km [R3.2.4]. Despite this higher resolution, the SDT recommends that swath widths for a high resolution imager be at least as large as the MGS MOC (3 km), with a desire for swath widths of 4–6 km. Given these specifications, the SDT recommends that a reasonable* <u>*goal*</u> *for MRO is that ~1% of the Martian surface be covered by high-resolution observations taken though both primary and extended missions [R3.1.5].*

Given this recommended spatial resolution for imaging and the MRO data-return capability, the size of the observed target areas may be small (~100 km^2). Thus, the question of context imaging arose, as it had for the imaging spectrometer [4.3]. In its consideration of the MARCI MA proposed for MSO, the SDT regarded its attributes—a three-color imager with a spatial resolution of 7.5 m/pixel (from 400 km altitude) and a swath width of 40 km—as nearly ideal for providing context to both an imaging spectrometer and a high-spatial-resolution camera. The proposed spatial resolution was a factor of 2 or more better than both THEMIS VIS and the globally extended imaging by the Mars Express High Resolution Stereo Camera (HRSC). Although capability for three-color imaging was not required, it was regarded as highly desired, and there was some sentiment that stereo capability be considered. However, the SDT recognized that changes beyond what was proposed for MSO could require resources outside the MARCI envelope (in mass and power) and might also jeopardize the MARCI WA investigation, which the SDT did endorse. *Thus, the SDT endorses flight of the MARCI MA with the capability (and resources) proposed for the '03 MSO, but as a facility instrument [R3.2.2].*

The recommendation to treat the (MSO) MARCI MA camera as a facility reflects *the judgment by the SDT that context imaging and processing must be coordinated with other science investigations [R3.1.1b]* and thus would be a resource on which instrument providers responding to the MRO AO can rely. This would prevent expenditure of resources on duplicate capabilities. (The SDT believes that it would be difficult to provide context imaging as described above for much less than the MARCI mass and power envelope.) An investigation providing context imaging as a facility—whether or not based on the MSO MARCI MA—should support the MRO high-resolution imager and imaging spectrometer investigations by: a) acquiring context images for each targeted high-spatial-resolution observation, and b) by transferring these data to their science teams in near-real-time in order to support sequence planning and later data analysis. Assuming a facility context imager with the MARCI capabilities, context imaging could cover several percent (≤ 10%) of the planet's surface.

4.5 Subsurface Sounding

The SDT recommends that the NASA Mars Exploration Program survey Mars with a comprehensive subsurface sounding package in the near future, but not necessarily on the MRO [R3.3.3]. If not on the MRO, such a subsurface sounding package should have very high priority for missions considered for the 2007 and 2009 launch opportunities. The detection of liquid water in the upper crust of Mars and the profiling of ice in the subsurface, particularly within 1 km of the surface, would be major discoveries in the exploration of Mars. Thus, it is not surprising that MEPAG gives subsurface sounding—including survey from orbit—very high priority in all three science areas (Life, Climate, Geology—see Appendix 2). Furthermore, there are radar systems whose requirements of <u>instrument</u> power and mass clearly fit within the MRO resource envelope (see Appendix 3).

There remain two major difficulties. First, we have no data to tell us what the subsurface of Mars is really like. Thus, we do not know today if the features that we seek (e.g., liquid water near the surface or, more likely, at depth; ice lens throughout the subsurface, with depth and thickness varying with latitude and location) are in fact there. If they are present, we do not know if our presently designed systems will yield their definitive detection and delineation. The subsurface may, for instance, attenuate the radar pulses far more than expected, or its layers and lenses of ice may be so convoluted that the radar return cannot be interpreted without independent information. Such information may not be acquired for some time (e.g., from a global surface seismic network or from deep drilling).

The first concerted effort to explore the Martian subsurface (i.e., the region below depths of a few centimeters to meters) will be flight of the Italian (ASI) – U.S. (NASA) Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) investigation. MARSIS will be flown on the ESA

Mars Express orbiter to be launched in 2003 and will begin returning data in 2004, which will be too late to impact materially the design of a radar for MRO. Even if MARSIS performs as expected (meaning that Mars is enough like our assumptions that its technical approach will succeed), its investigation is likely to probe only a small part of the planet's surface. This is due to: a) the limited time available for MARSIS observations in the highly elliptical, sun drifting Mars Express orbit; b) the difficulty of correcting dayside observations for ionospheric effects; and c) the constrained spacecraft data downlink rate and the competition for it with the other, often high-data-rate, Mars Express instruments. Most of these restrictions on Mars Express are greatly eased by the orbit recommended for MRO and by the projected improvements in spacecraft downlink capability.

However, there are other accommodation issues, in particular the impact of electromagnetic interference (EMI), as it restricts the operation of the radar and other instruments. EMI concerns include possible interference between the radar and the spacecraft (particularly its telecommunication and electrical systems), as well as EMI between the radar and other instruments. Operational constraints may alleviate some difficulties, in that a radar system operating routinely only at night would have less interference with optical instruments observing reflected sunlight. However, atmospheric sounders, such as the PMIRR-MkII, need to operate essentially continuously—day and night—to achieve their science goals and yet they may be susceptible to radar-generated EMI. *The SDT recommends that the MRO Project ensure that EMI not preclude acquisition of key data by the science instruments [R3.1.2b].* (There are similar concerns of EMI between the payload and the UHF package used to support landed spacecraft. At present, the MRO Project plans to deal with these operationally by requiring that science instruments generating or susceptible to EMI with the UHF will be off when the UHF is actively operating. However, the UHF relay periods are relatively short in duration. This flight rule should be noted in the AO or its supporting information package.)

Another issue is the accommodation, orientation and stability of the radar antennae required for subsurface sounding. The stability concern arises when the spacecraft moves to point off-nadir, as it may do to provide high-resolution observing of a targeted zone not on the spacecraft track. Short settling times may not be a problem. Orientation is a concern if a particular geometry is required with respect to the movement and support of the solar arrays and high gain antenna.

The degree of difficulty in accommodation is highly dependent on the radar's operating frequencies, the location on the spacecraft deck, and the degree of mitigation in the design of the spacecraft systems. The lowest frequencies (< 1 MHz) are likely to generate the most interference, and also require the longest antenna for operation. (The longest antenna is likely to produce the most spacecraft jitter.) Frequencies < 1 MHz on MARSIS are essentially used to study the dayside ionosphere for scientific reasons and to remove its effects on the higher-frequency, subsurface sounding modes. Frequencies > 5 MHz are needed for near-surface (< 1 km) profiling, but a dual-mode radar with somewhat lower frequencies will be required to probe deeper and may be required for even the topmost kilometer of subsurface, depending on its composition and compaction.

The SDT has little doubt that these issues can be dealt with successfully, but it may take a spacecraft design which <u>starts</u> with a focus on the subsurface sounding capability. In effect, similar to the ultra-high-resolution camera discussed earlier, the proper subsurface sounding investigation may require a dedicated mission. Because the current MRO spacecraft design builds, by NASA directive, on the '03 Mars Surveyor Orbiter Study—which did not include a radar system—these accommodation issues are of greater concern.

In summary, the SDT recommends that a subsurface sounder be considered for the MRO payload [R3.3.4]. The SDT further recommends that the MRO Project continue to study accommodation issues, providing a clear statement for the AO what the likely operational constraints for a subsurface sounding radar are likely to be. For instance, operations are presently to be limited to the nightside to avoid ionospheric effects and interference with dayside targeting (this does not avoid potential interference with the atmospheric instruments), <u>and</u> to times when the spacecraft is not returning data to Earth. These are formidable limitations on a spacecraft that is baselined to spend 16 hours a day downlinking data to Earth. It is the potential scientific gain of detecting subsurface water that makes subsurface sounding still worth considering in the 2005 launch opportunity.

4.6 Gravity and Other Studies

Variations in the Martian gravity field reflect interior density variations, thereby providing insight into the planet's crustal structure and its tectonic history. The routine tracking by the DSN of spacecraft in low-altitude orbits around Mars provides the data needed to precisely reconstruct orbits from which perturbations due to gravity anomalies within the planet can be derived. Tracking of the Mars Global Surveyor has provided a much improved gravity field, modeled now to an equivalent half-wavelength of 140 km (i.e., to spherical harmonics of degree and order 60–75). Significant improvement in these new gravity models requires observations at altitudes ≤ 300 km. Normal two-way Doppler tracking (with ranging) of the MRO in the recommended 200 x 400 km orbit could improve the spatial resolution of the MGS-derived gravity models by a factor of two, and this would be scientifically significant. (Note that the gravity studies do not require the ultrastable oscillator discussed earlier [4.2].) Since the baseline MRO primary mission presently assumes two 8-hour passes to 34 m DSN ground stations, there should be ample tracking time to provide the required gravity data.

Tracking MRO during its aerobraking phase may also provide useful data, but communications with the spacecraft are likely to be limited during the aeropass itself, at altitudes below 200 km. Moreover, these low aeropass altitudes will be limited to the polar regions. Thus, *the SDT recommends the selection of a gravity investigation only if the spacecraft altitude is ≤ 300 km for significant periods during the primary mission [R3.3.2]*, as would be the case for the recommended elliptical orbit (or a near-circular 300 km orbit). In that orbit the periapsis latitude rotates around the planet every 60 days or so. This provides global coverage and opportunities for gravity "campaigns" when the best geometry for gravity studies occurs (i.e., when low-altitude tracking occurs with the Earth-spacecraft line < 70˚ from the spacecraft nadir axis). Given that the radio science investigation for gravity does not require additional hardware and adds little operational complexity, *the SDT recommends that a gravity investigation be selected for MRO through the AO process, if science funding permits [R3.3.2]*.

The SDT subgroups also considered the rationale for observations by a magnetometer onboard the MRO. The MGS magnetometer observations during aerobraking revealed an unexpected and very strong pattern of crustal remnant magnetism. To improve upon the MGS data would require additional magnetic measurements below the ionospheric peak (~ 150 km), which essentially means during the aerobraking phase of the MRO mission. The duration of MRO aerobraking is presently projected to be less than three months, its periapsis altitudes will not be significantly lower than MGS (providing no improvement in spatial resolution), and the periapsis latitudes will be restricted to the polar regions (poleward of 60˚S).

Spacecraft accommodation issues are not as intimidating as they once were for magnetometer experiments. For MGS, close cooperation between the magnetometer science team and the spacecraft contractor early in the design phase pioneered an approach in which the magnetometers were placed near the ends of the power-generating solar array panels (eliminating booms) and still achieved immensely improved magnetic sensitivity over that on Mars Observer. Even so, given the limited opportunity for observations and the suite of other potential accommodation issues for the spacecraft development, *the SDT does not recommend that a magnetometer be flown on MRO*. Magnetic measurements should continue to be considered in future missions that can accommodate the need for both horizontal coverage and low-altitude observational sensitivity.

Flight of a magnetometer could also advance our understanding of the solar wind interaction with the planet and its role in the loss of atmospheric gases, especially the components of water vapor, to space. While MEPAG identified the need to better understand this escape loss, it was at lower priority than other investigations (CA4, Appendix 2). Furthermore, the NOZOMI and Mars Express missions have several very capable instruments observing the upper atmosphere of Mars from advantageous orbits (highly elliptical, with extensive local time coverage). Their observations should start in 2004, a time when solar cycle activity will approach its minimum, while MRO observations would occur just after that minimum. As was the case for upper atmosphere remote sensing [4.2], *the SDT does not recommend that atmospheric escape (and thus a magnetometer) be given high priority in the scientific goals for MRO. The SDT does recommend that such investigations be considered for a later mission that observes Mars when solar cycle activity is near its maximum.*

One final area explored by the SDT and its subgroups was what might one do with thermal infrared imaging, given the considerable capability of the 2001 Mars Odyssey THEMIS infrared experiment. To go beyond the 100 m footprint resolution of THEMIS requires a large aperture to get beyond the diffraction limit at thermal infrared wavelengths, raising the possibility of using the “light bucket” of the high-resolution imager. The science goal would be to use a thermal IR imager to detect very localized (~10 m diameter) “hot spots” on Mars [R3.3.7]. Such a device would look globally at night, only returning data when it sensed a significant anomaly against the IR background already established by the MGS TES and (soon) by the THEMIS investigations. Such detection would scientifically be very important, in that the existence of such areas would be established and these sites would quickly become targets for further orbital and landed exploration. The likelihood of such detection is small, but warrants some consideration within the framework of the Group II science objectives.

5.0 PROGRAMMATIC ISSUES

5.1 Selection as Facility or PI Instrument

The SDT recommends that all the science instruments, with the exception of the MARCI Medium Angle camera, be flown as PI-provided investigations [R3.4.1, R3.4.4b]. Thus, the NASA AO should invite the scientific community to bring innovative, science-focused investigations that address the MRO objectives, but which also give serious consideration to the technical challenges associated with the schedule for launch of the MRO in 2005. For facility science teams (e.g., for analysis of accelerometer, gravity, or radio occultation data), *the SDT recommends that the team leaders be brought on as soon as possible [R3.4.4c]* to help advise the spacecraft and ground data system development. This will ensure that the best quality science data are obtained within the constraints of spacecraft schedule and mission funding.

The preference for PI-provided instruments should be revisited, if NASA chooses an MRO investigation whose demands on the spacecraft are beyond those recommended here; e.g., a very heavy and/or very large camera or radar. The SDT briefly considered the prospect of a facility telescope, with back-planes for visible and thermal infrared imaging and for visible and near-infrared imaging spectrometry. The technical complexity—and risk—of such arrangements within the schedule and funding constraints of an MRO for launch in 2005 are daunting. The SDT did not pursue this concept any further.

The reasons for recommending that the MARCI MA designed for the ’03 MSO be a facility were discussed above [4.4]. Some members of the SDT were troubled by this exception, and there was concern that the SDT had not given the MARCI team the same latitude in redesign as had been given PMIRR. The SDT majority believed it reasonable to distinguish between the two (and between the objectives for MARCI WA and MA) given the THEMIS VIS capability. The SDT did believe that the MSO MARCI MA design met the requirements for context imaging [R3.2.2]. In that regard, the SDT believed that a context imager should be designated as a facility in order that context imaging be reliably provided in support of MRO targeting. Even so, a significant degree of coordination between the targeting instruments is still required. *The SDT recommends that the MRO Project Science Group (PSG) should coordinate the choice of targeted sites [R3.4.2c].* The SDT anticipates that some fraction of the targets should be viewed by more than one instrument (in addition to context imaging) and that some targets will be dictated by the needs of the Mars Exploration Program (e.g., landing sites for near-term missions). There is great benefit in having high-resolution and imaging spectrometry (with context imaging) of the same place [R3.1.1b]. Since there are a limited number of observation opportunities (limited by the downlink capability), choices will have to be made. However, some significant fraction of targets should be at the sole discretion of the PI.

5.2 Ground Data System

The anticipated data volume to be returned by the MRO (~ 24 Tbits in 1 Mars Year) is enormous by comparison to previous Mars missions. When annotated and combined with ancillary data, this data volume is increased by an order of magnitude. The generation of geophysical and mapped data products typically increases this by another order of magnitude. The distribution of such huge data sets may require a different approach than the one used successfully by MGS science investigators and planned for use by the 2001 Mars Odyssey Project. In this MGS strategy, data moves from the DSN to JPL and is distributed to the Principal Investigators at their home institutions for all routine and special processing. The PI is then responsible for distribution to his or her co-investigators and to other Project science personnel, as negotiated. The PI is also responsible for return of the standard data products to the appropriate Planetary Data System nodes for archive. (The JPL Multi-Mission Organization—successor to the Mars Surveyor Operations Project—is responsible for archiving the raw data.) The MRO data volumes will require the planned upgrades of the telecom links that transfer data from the DSN stations to JPL.

The MRO Project Team proposed consideration of a data distribution scheme in which much of the data processing is done on machines at JPL, using software provided by the Science Investigators and with the data processing under their control (e.g., the scheduling of large production processing runs). The central processing facility would be a backup to the usual structure, with a network of lines between the science teams and JPL provided as before. Thus, commands for instruments would still originate from the PI-institutions and enough “quick-look” data would be transferred to the PI-sites that they would know the quality and status of the instrument operations and of the centralized data processing.

The SDT understands the concern that the MGS model for the distribution and processing of Mars data is not adequate for the MRO mission. *However, the SDT recommends that the Project first see if there is a way to implement the MGS data distribution system [R3.4.3b]*, with the DSN and JPL transferring instrument data as they are received to each PI at his or her host institution. If it occurs that there are instruments where this is not adequate (presumably those with the highest data rate), it is reasonable for NASA and JPL to consider processing the high-volume data sets at a central facility and distributing the products on appropriate media.

Once formed, the MRO Project Science Group should be fully involved in these discussions. *The SDT recommends that the guiding principle should remain PI-control [R3.4.3b] of the data processing, including control of the distribution of raw data and control of data processing, as consistent with the NASA Mars Exploration Program data rights policies.*

5.3 Data Rights

The SDT did not discuss the issue of data rights and responsibilities to any degree, *as the SDT assumed that the now standard Mars Program policy would guide the MRO Project and investigators [R3.4.3c]*, and that this would be stated in the AO. The SDT does support the policy of early data release, particularly for public outreach, even as it understands that in some cases there will be elaborate calibration and tuning of the data processing approach before reliable products can be released. There will be even more need in this mission for interaction between the science teams and thus for rapid exchange of data between them. The targeted nature of the high-spatial-resolution observations will require decisions on which sites to target and whether or not the data acquired were adequate.

The SDT recommends that MRO Project Science Group adjudicate these decisions and other potential conflicts that might arise between science investigations [R3.4.2b].

5.4 Augmentation of Science Teams

The discussion here centered on three topics: a) should the AO solicit additional team members for the MCO re-flight instruments; b) should participating scientist or guest investigators be added to the MRO mission, and if so, when should they be funded; and c) what should be the nature of interdisciplinary investigations?

On the first topic, the SDT recommends that the AO <u>not</u> solicit additional team members for PMIRR and for MARCI (WA) [R3.4.4a], as it could compromise the roles of existing team members and distort what were selected as PI-led investigations for no clear benefit. If there are positions that need to be filled, the PI should approach NASA (and vice versa) in the normal way.

With regard to the second topic, the SDT recommends that additional investigators (e.g., Participating Scientists) should be solicited by an AO no earlier than one year before arrival at Mars, with members coming onboard no later than just before launch [R3.4.4d]. (As noted earlier, team leaders of facility teams should be added at the same time as other science teams.)

With regard to the third topic, the SDT recommends that NASA explore the possibility of adding interdisciplinary investigators at the program level (i.e., across individual mission boundaries) [R3.4.4e] when there are compelling reasons to do so.

5.5 Funding of MRO Science

The SDT did not discuss funding of the MRO mission in any detail, as the Project presented no details. However, the Project did state that the funds available for the science payload and for science analysis were essentially those budgeted in the ’03 MSO study done last summer (with adjustments for inflation). This raises a number of concerns. First, the investigations selected for MSO emphasized mature design and direct flight hardware heritage. This was necessary because of the short development schedule dictated by an ’03 launch, but it did potentially compromise the science investigations relative to the requirements recommended here. (The degree of compromise can only be judged against the responses to the AO.)

At any rate, the instruments selected as part of an AO response are unlikely to require less development time than those deliberately selected emphasizing flight heritage, and so the instrument payload funding requirements may have been underestimated. Second, the discoveries from MGS during the last several months have given new emphasis to the exploration of the subsurface and characterization at high spatial resolution of the surface composition and morphology. Given the SDT recommendations, instruments likely to be proposed in response to the AO may well have significant technical issues of instrument development and spacecraft accommodation. These developments may exceed the inflation-adjusted cost estimates for science investigations. Selection of such instruments should be done so that they fit within the resource box, either by providing additional funding or by restricting selection. *If the latter, the SDT recommends that only instruments which meet or exceed the minimum requirements discussed here be selected.*

Selection and funding of the facility teams that were recommended by the SDT to analyze data in support of the Group II science objectives should be weighed carefully against other uses and benefits of the limited MRO science funding. Even though these investigations require no addition of hardware to the spacecraft, their overall costs can be high (e.g., the radio science investigation—including both gravity and atmospheric profiling—was the second most expensive investigation on MGS). Thus, their selection needs to be judged in the context of the apparently limited MRO science funding.

Finally, the MSO study never had time to come to grips with the effort required to handle the vast quantities of data that the MSO and MRO missions will return. As discussed above, merely moving the data around presents some serious challenges. Furthermore, the SDT doubts that the full cost required to analyze these tremendous data sets, including provision of products needed for site selection for the ’07 Mars missions, is covered by the MSO-based science budget.

The SDT recommends that NASA, the JPL Mars Program, and the MRO Project give special attention to understanding and covering all legitimate costs of data distribution, processing and analysis [R3.4.3a]. These factors need to be known prior to final selection of the payload, as the Mission may find that its most critically limited resource is funding, not payload mass or power.

APPENDIX 1

MRO Science Definition Team (SDT)

SDT Members	Affiliations
Richard Zurek (Co-Chair)	Jet Propulsion Lab/Caltech
Ron Greeley (Co-Chair)	Arizona State University
Jeffrey Barnes	Oregon State University
Stephen Bougher	Lunar and Planetary Lab, University of Arizona
Fabrizio Capaccioni	CNR (Italy)
Michael Carr	U. S. Geological Survey
Philip Christensen	Arizona State University
Stephen Clifford	Lunar and Planetary Institute
Angioletta Coradini	CNR (Italy)
R. Todd Clancy	Space Science Institute
Jack Farmer	Arizona State University
Laurie Leshin	Arizona State University
Glenn MacPherson	Smithsonian Institute
Mike Malin*	Malin Space Science Systems
Phillipe Masson*	U. Paris Sud, LGD
Scott Murchie	Applied Physics Lab/Johns Hopkins University
John Mustard	Brown University
Patrick Pinet	CNES (France)
R. Keith Raney	Applied Physics Lab/Johns Hopkins University
Mark Richardson	California Institute of Technology
Suzanne Smrekar	Jet Propulsion Lab/Caltech
Larry Soderblom*	U. S. Geological Survey
Ex Officio Members	**Affiliations**
James B. Garvin	Mars Program Scientist, NASA Headquarters
Ramon P. DePaula	MRO Program Executive, NASA Headquarters
David Senske	MRO Program Scientist, NASA Headquarters
Daniel J. McCleese	Chief Scientist, JPL Mars Program Office, JPL/Caltech
James E. Graf	MRO Project Manager, JPL/Caltech
* Notes: • M. Malin participated in the January 18–20 meeting by telephone • L. Soderblom and P. Masson were unable to participate in the January 18–20 meeting.	

APPENDIX 2

TRACING MRO REQUIREMENTS TO MEPAG RECOMMENDATIONS

Listed below in Table A2-2 are the goals, objectives, and investigations identified in the MEPAG report, together with the remote sensing measurements identified by MEPAG as necessary to accomplish the science investigations. The listing here preserves the priority listing of objectives and investigations by MEPAG. Note, however, that there was no attempt by MEPAG to prioritize across the Life, Climate, and Geology goals. In some cases the priority order of investigations reflects assessments of technical difficulty, so that some measurements may be elevated in priority for a particular mission opportunity depending on the timeliness of the technical approach.

Some investigations do not require further orbital remote sensing, beyond data that have already been returned (e.g., Viking, MGS) or that are expected from missions now proceeding to flight (e.g., 2001 Mars Odyssey and Mars Express). Also, many investigations require additional measurements not listed in the Table below, such as measurements from low-altitude aerial platforms, from landed stations (including roving vehicles and surface networks), or on rock, soil and air samples returned from Mars to Earth. Only measurements requiring remote sensing from orbit are highlighted here, although all MEPAG investigations are listed in Table A2-2. The reader is referred to the full MEPAG document for other details (MEPAG, 2000, *Mars Exploration Program: Scientific Goals, Objectives, and Priorities*).

However, it can be seen from the MEPAG recommendations that most of the orbital measurement requirements fall into a few major categories. These are shown in Table A2-1 and were also captured in the proposed Group I and Group II science objectives [Section 2]. These objectives motivated the recommendations of the SDT [Section 3]. In Table A2-1 the first sub-bullet after each science goal cross-references the MEPAG goals/objectives/investigations shown in Table A2-2, where there is a more detailed comparison of the recommended MRO capabilities against the MEPAG required measurements. Investigations in parentheses in Table A2-1—e.g., (LA3)—are indirectly or only partially addressed by the MRO payload.

The second sub-bullet after each science goal in Table A2-1 indicates generic instruments or investigations (the MCO instruments are identified by name) that the SDT believes can substantially address the science thrust. The entries in this sub-bullet are listed roughly in priority order, although much depends upon the exact capabilities of the proposed investigations.

Note that in Table A2–2, the range of spatial resolutions for MRO imaging instruments is based on the recommended capabilities assuming observations from orbital altitudes of 200–400 km (e.g., 30–60 cm/pixel for the high-resolution imager).

TABLE A2-1

Science Objectives and MRO Measurements

- Mapping the atmospheric seasonal cycles of water, dust, and carbon dioxide;

  LA1, (LA3), CA1, CA3, (CA5), (CA6), (GA5)
  PMIRR, MARCI WA, Submillimeter Sounder

- Detecting subsurface liquid water and mapping the subsurface ice distribution;

  LA1, LA2, (LA3), (LA4), CA1, (CA5), GA1
  Subsurface Sounder (Radar)

- Identifying sites with evidence of aqueous mineralization and sedimentation;

  LB1, LB2, LB3, LC1, LC2, CB1, CB2, GA2, GA5
  Visible Near-Infrared Imaging Spectrometer, High-Resolution Imager, Context Imager (e.g., the MSO MARCI-MA)

- Understanding the stratigraphy and morphology of the surface in enough detail to understand the presence & timing of aqueous processes;

  LB3, LC2, CB1, CB2, GA2, GA3, GA4, GA5, GA8
  High-Resolution Imager, Context Imager, Imaging Spectrometer

- Achieving a broader scientific and engineering understanding of the planet;

  CA4, CA6, GA6 (gravity), GA7 (gravity), GA8, GB1-GB3 (gravity only)
  Gravity Studies, Accelerometer Analysis, Radio Science

- Objectives not addressed by recommended MRO remote sensing.

  (LA3), LA4, LA5, LA6, CA2, CA4, (CA5), (CA6), GB1-GB3 (magnetometry)

Table A2-2: MEPAG Recommendations for Orbital Remote Sensing

MEPAG GOAL (G) **Objectives (X)** Investigations (GX#)	**Observations from Orbit needed to support MEPAG Mars Exploration Program Science Goals** ***MRO Capabilities in Italics***
LIFE (L)	
Objective A: Present Life	
LA1 3-D Water Distribution	Global Survey: Atmosphere, surface, subsurface, ice caps *MRO: Atmospheric survey with PMIRR & MARCI-WA* *MRO: Subsurface water search, if radar is selected.*
LA2 In Situ search for liquid water	Determine sites to search in situ for liquid water. *MRO: Search for liquid water if subsurface sounder (radar) selected.*
LA3: Explore high priority sites for extant life	Determine sites with greatest potential—find locales with water and energy today. *MRO addresses through search for water (see above).*
LA4: Determine energy sources for biologic processes	Find geothermal “hot spots” or “wet zones”. *MRO addresses through search for water (see above), but at coarse spatial resolution.*
LA5: Nature of organic carbon in soils and ices	Determine sites for in situ surface analysis and potential sample return. *MRO does not address.*
LA6: Determine oxidants and their relation to organics	Not approached with observations from orbit. *MRO does not address.*
Objective B: Past Life	
LB1: Locate aqueous sedimentary deposits	30 m/pixel visible imaging; 40 m/pixel hyperspectral mapping of aqueous sediments. *MRO Context Imaging: 5–10 m/pixel (MARCI MA)* *MRO Imaging Spectrometry: 25–50 m/pixel*
LB2: Search for Martian fossils	20 m/pixel visible imaging; 40 m/pixel hyperspectral mapping of aqueous sediments. *MRO Context Imaging: 5–10 m/pixel (MARCI MA)* *MRO Imaging Spectrometry: 25–50 m/pixel* *MRO High-Resolution Imager: 30–60 cm/pixel*
LB3: Timing and duration of hydrologic activity	Find aqueous mineral deposits and diagnostic sedimentary structures. *MRO Imaging Spectrometry: 25–50 m/pixel* *MRO High-Resolution Imager: 30–60 cm/pixel* *MRO Context Imaging: 5–10 m/pixel (MARCI MA)*
Objective C: Pre-Biology	
LC1: Search for complex organic molecules in rock/soil	Find modern aqueous environments and paleo-environments. *MRO Imaging Spectrometry: 25–50 m/pixel* *MRO High-Resolution Imager: 30–60 cm/pixel* *MRO Context Imaging: 5–10 m/pixel (MARCI MA)*

LC2: History of change in organic carbon inventories	Establish correlations and a stratigraphic framework: 1 m/pixel visible imaging; 40 m/pixel near-IR imaging spectrometry. *MRO High-Resolution Imager: 30–60 cm/pixel* *MRO Context Imaging: 5–10 m/pixel (MARCI MA)* *MRO Imaging Spectrometry: 25–50 m/pixel*

CLIMATE (C)	***Measurements from Orbit***
Objective A: Present Climate	
CA1: Processes controlling water, dust, and CO_2 cycles	Observe seasonal & daily cycles of water, dust, & carbon dioxide in the atmosphere and on the surface; Global atmosphere, ~5 km vert. x 5˚ lat. x 30˚ long. for at least 1 Mars year. *MRO achieves with PMIRR and MARCI WA.* Map near-surface groundwater and ice; detect subsurface water (near-surface < 100 m at 10 m vert. res.; deep < 5 km at 100 m vert. res.). *MRO achieves if radar flown.*
CA2: Stable isotopic and noble gas composition	Insufficient precision in orbital remote sensing. *MRO can not address.*
CA3: Long-term trends in climate (T, dust, water, CO_2)	Observe seasonal cycles of water, dust, carbon dioxide & temperature over several Mars years. *MRO PMIRR and MARCI observations can be compared with Mariner 9, Viking and Mars Global Surveyor data.*
CA4: Rates and processes of atmospheric escape	Map global distributions of upper atmospheric H, O, CO, CO_2 and key isotopes over seasonal and solar cycle variations; correlate with lower atmosphere processes (e.g., dust storms). *MRO would not address*.
CA5: Search for microclimates	Detect “hot spots” or local concentrations of water vapor in locales of dimension ~100 m. *MRO unlikely to detect if source is small or intermittent.*
CA6: Photochemical processes	Measure key trace gases and transient changes; requires ultra-high-spectral/spatial atmospheric profilers. *MRO contributes some by tracking water (PMIRR) and ozone (MARCI-WA), but does not provide high precision.*
Objective B: Past Climate	
CB1: Find physical & chemical records of the past	Remote sensing of hundreds of targets in the visible at resolutions up to 15 cm/pixel; with adequate context imaging; hyperspectral remote sensing at 20–50 m/pixel. *MRO would observe hundreds of targets* *MRO High-Resolution Imager: 30–60 cm/pixel* *MRO Context Imaging: 5–10 m/pixel (MARCI MA)* *MRO Imaging Spectrometry: 25–50 m/pixel*

CB2: Characterize history of past climate change	Remote sensing of hundreds of targets in the visible at resolutions up to 15 cm/pixel; with adequate context imaging; hyperspectral remote sensing at 20–50 m/pixel; near-IR spectra should extend to ~ 4 microns. *MRO would observe hundreds of targets* *MRO Imaging Spectrometry: 25–50 m/pixel, 0.4–3.6 mcrn* *MRO High-Resolution Imager: 30–60 cm/pixel* *MRO Context Imaging: 5–10 m/pixel (MARCI MA)*

GEOLOGY (G)	***Measurements from Orbit***
Objective A: Surface Geology	
GA1: Present state of water on Mars	Global search for water to depths of several kilometers with 100 m horizontal & vertical spatial scales. *MRO addresses if subsurface sounder (radar) flown, although possibly at more coarse horizontal scale (≥ 1 km).*
GA2: Evaluate sedimentary processes through time	Global stereo imaging ≤ 10 m/pixel and contiguous regional coverage; at least 1 % of planet at better than 1 m. Visible near-IR imaging spectrometry, with 10 wave-number spectral and 30 m/pixel spatial resolution. *MRO Imaging Spectrometer: 25–50 m/pixel* *MRO High-Resolution Imager: 30–60 cm/pixel* *MRO Context Imaging: 5–10 m/pixel (MARCI MA)* *No stereo in baseline, but could be added.* *Coverage goal is ~ 1%, assuming extended mission*
GA3: Calibrate cratering record and absolute ages	Record based on imaging from orbit; age calibration requires in situ analysis or sample return. *MRO addresses through high-resolution and context imaging.*
GA4: Evaluate igneous processes and history	Imaging (including stereo) at ~ 1 m/pixel with ~10 m/pixel context imaging. Hyperspectral data with 30m/pixel resolution of key igneous regions (~20% of Mars surface). *MRO Imaging Spectrometer: 25–50 m/pixel* *MRO High-Resolution Imager: 30–60 cm/pixel* *MRO Context Imaging: 5–10 m/pixel (MARCI MA)* *No stereo in baseline—rely on Mars Express?* *Coverage goal is ~ 1% (<10% for context imaging), assuming extended mission.*

GA5: Characterize surface-atmosphere interactions	Stereo imaging (~ 1 m/pixel with ~10 m/pixel context); Hyperspectral data with 30 m/pixel resolution of key regions (~20% of Mars surface). *MRO Imaging Spectrometer: 25–50 m/pixel* *MRO High-Resolution Imager: 30–60 cm/pixel* *MRO Context Imaging: 5–10 m/pixel (MARCI MA)* *No stereo in baseline, but could be added.* *Coverage goal is ~ 1% (<10% for context imaging), assuming extended mission.* Global Synthetic Aperture Radar (SAR) mapping of subsurface structures at depths up to several meters and at resolutions ~ 100 m/pixel. *There are no plans for MRO to fly a SAR.*
GA6: Determine structure and composition of the crust	Same orbital remote sensing as GA5 plus global gravity survey as in GB1. *MRO may increase resolution of gravity model by a factor of 2.*
GA7: Document tectonic history of the crust	Same as GA5 plus global gravity survey as in GB1 and global magnetic survey as in GB2 *MRO may increase spatial resolution of gravity model by a factor of 2. No magnetometer is recommended for MRO.*
GA8: Evaluate the role of impact and volcanic hydrothermal activity	Global and detailed imaging to search for and characterize candidate volcanic and impact features. *MRO High-Resolution Imager: 30–60 cm/pixel* *MRO Context Imaging: 5–10 m/pixel (MARCI MA)* *No stereo in baseline—rely on Mars Express?* *Coverage goal is ~ 1% (10% for context imaging), assuming extended mission*

Objective B: Mars Interior	
GB1: Characterize the configuration of the interior	Global gravity survey to 10 mgal precision to wavelength resolution of 175 km; requires tracking of spacecraft at low altitude (~200 km). Global magnetic survey as in GB2. *MRO may increase spatial resolution of gravity model by a factor of 2. No magnetometer is recommended for MRO.*
GB2: Determine the history of the magnetic field	Global magnetic survey with 0.5 nT accuracy and spacing < 50 km; requires observations from altitudes < 120 km. *No magnetometer is recommended for MRO.*
GB3: Determine chemical & thermal evolution of Mars	Global gravity and magnetic measurements as in GB1 and GB2. *MRO may increase spatial resolution of gravity model by a factor of 2. No magnetometer is recommended for MRO.*

APPENDIX 3

SAMPLE PAYLOADS

The SDT considered a number of sample payloads in order to assure that there were a number of scientifically credible payloads that fit within the resource envelope of the present MRO mission concept. These considerations are necessary preliminary, as both the payload and the spacecraft will be selected in response to an AO and RFP, respectively, both to be released in the near future. *In particular, these are not recommended allocations.*

Table A3-1: Sample Payload Estimated Masses (kg)

	A	B	C	D	E	F
PMIRR	7	7	7	7	7	7
MARCI	3	3	3	3	3	3
VISNIR	23	20	23	23	23	23
HRI	40	37	40	20 (MOC*)	20 (MOC*)	37
RADAR	22	18	-	22	18	-
Sub-MM	9	-	9	9	-	-
TOTAL	104**	85	82	84	71	70

* MOC-like spatial resolution does not meet Group I objective
**Does not fit in any existing MRO payload mass projection

In the above table, PMIRR is the redesigned PMIRR-MkII and MARCI includes both the Wide and Medium Angle Cameras. VISNIR refers to a visible near-infrared imaging spectrometer. HRI denotes a high-spatial-resolution imager (the mass estimated by the JPL Project for a 60 cm/pixel ground resolution camera observing from 400 km altitude). RADAR denotes a subsurface radar sounder, with a “near-surface” mode only (estimated at 18 kg) and a dual mode (estimated at 22 kg) system designed to penetrate up to 5 km deep. (No distinction was made for possible differences in radar antenna mass or shielding—those differences may be significant [4.5].) The last entry, Sub-MM, was meant to represent atmospheric sounders complementary to PMIRR and was based on a submillimeter limb sounder design based on the ROSETTA MIRO technology and an earlier Mars Express proposal. No mass allocation was given to accelerometer science or radio science (i.e., the USO for atmospheric science), as the SDT does not recommend these investigations if the hardware must be taken from the payload allocation.

The JPL Project provided two target payload masses from the reference design studies—70 kg and 86 kg—depending upon aerobraking options (and associated fuel loads) to be decided after further study.

As is readily seen, List A is nearly 20 kg over even the larger of the two projected payload masses and cannot be accommodated by any existing MRO payload mass projection. (Even should a larger launch vehicle be magically provided, it is not clear that the MRO funding could support development and flight of all instruments on List A.)

List B fits the larger mass envelope by eliminating the submillimeter sounder, reverting to the near-surface radar, and assuming modest reductions in the projected masses of the imaging spectrometer and high-resolution camera. List C eliminates the radar completely, preserving the mass allocations of other instruments, while emphasizing mapping of atmospheric water. List D flies an MOC-quality imager whose gain in spatial resolution (70 cm/pixel from 200 km) is less than the desired factor of 3; this option does include, however, the dual-mode radar.

Fitting inside the 70 kg payload box is more difficult. List E removes the submillimeter sounder, the deep subsurface mode for the radar, and reverts to the MOC-class imager. List F eliminates the radar and submillimeter investigations completely. List F is essentially the MSO designated payload, minus the UV Imaging Spectrometer. The smaller payload mass (than for the '03 MSO) reflects the more demanding celestial mechanics of the 2005 launch opportunity over those of 2003. Differences between Lists E and F also would ultimately reflect spacecraft accommodation issues—including cost—of a large imager or of a subsurface radar, and this is not reflected in Table A3-1. Lists B, C, and F potentially address each Group I science objective, but possibly none (List F) of the Group II objectives (except the radio science gravity, the accelerometer and possibly the radio science atmospheric occultation investigations).

The SDT drew the following conclusions from these comparisons. 1) There are several scientifically credible payload combinations within the MRO resource envelope [B, C, F], but they all involve the deletion of one or more of the Group II investigations. 2) Not all instrument combinations do achieve all Group I objectives and these are not recommended [Lists D, E]; 3) No one instrument should take more than half the payload mass, if MRO is to address all Group I science objectives.

APPENDIX 4

List of Acronyms

AO	NASA Announcement of Opportunity for MRO science selection
ASI	Italian Space Agency
CNES	French Space Agency
COMPLEX	National Research Council Space Studies Board Committee on Planetary and Lunar Exploration
DSN	Deep Space Network
ESA	European Space Agency
EMI	Electro-Magnetic Interference
HRSC	Super/High-Resolution Stereo Colour Imager (To be launched on Mars Express in 2003)
JPL	Jet Propulsion Laboratory, California Institute of Technology
MARCI	Mars Color Imager (Two-camera system lost with Mars Climate Orbiter; see next two entries)
MARCI WA	The MARCI Wide Angle camera designed for climate studies (A build-to-print duplicate is proposed for re-flight on MRO)
MARCI MA	A redesigned MARCI Medium Angle (moderate resolution) multicolor camera
MARSIS	Mars Advanced Radar for Subsurface and Ionospheric Sounding (To be launched on the ESA Mars Express orbiter in 2003)
MCO	Mars Climate Orbiter (Lost in 1999 during orbit insertion at Mars)
MEP	Mars Exploration Program
MEPAG	Mars Exploration Payload Analysis Group
MGS	Mars Global Surveyor (Now flying in Mars orbit in an extended mission)
MIRO	Microwave Instrument for the ROSETTA Mission (now in build)
MOC	Mars Orbiter Camera (Now observing from MGS in Mars orbit)
MRO	Mars Reconnaissance Orbiter, to be launched in the 2005 Mars launch opportunity
MSO	Mars Surveyor Orbiter (Studied for ’03 Launch Opportunity)
NASA	National Aeronautics and Space Administration
NOZOMI	Japanese Orbiter to arrive in Mars orbit in 2004 (formerly PLANET-B)
OMEGA	Infrared Mineralogical Mapping Spectrometer (To be launched on Mars Express in 2003)
PFS	Planetary Fourier Spectrometer (To be launched on Mars Express in 2003)
PI	Principal Investigator (For flight instrument)
PMIRR	Pressure Modulator Infrared Radiometer (Lost at orbit insertion on Mars Observer and Mars Climate Orbiter)
PMIRR-MkII	An Infrared Radiometer designed to capture PMIRR science objectives
PSG	Project Science Group
RFP	Request for Proposals to provide the MRO spacecraft for launch in 2005
SDT	Science Definition Team
SNR	Signal-to-Noise
TES	Thermal Emission Spectrometer (Now observing from MGS in Mars orbit)
THEMIS	Thermal emission and visible imaging experiment on the 2001 Mars Odyssey
UHF	Ultra-High Frequency relay antenna (Used for Orbiter-to-Lander telecom)
USO	Ultra-Stable Oscillator (required for radio occultation profiling on s/c egress)
VIS	THEMIS Visual Imager (To be launched in April 2001 on Mars Odyssey)
’01MO	2001 Mars Odyssey (To be launched in April 2001)